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Because of the ineffectiveness of the commonly used failure criteria, current analysis methods fail to accurately predict the strength of bonded composite joints. This analytical shortfall results in overly conservative joint designs. In a composite bonded joint, failure typically occurs in the first ply of the parent laminate near the stress singularity. In this study, and average strain approach is used to analyze this area and the first strain invariant failure criterion, also called the J_1 failure criterion, is adopted to predict the failure load of composite bonded joints. The analysis is based on a plane strain two-dimensional finite element model, which includes both the effects of geometric and material nonlinearity. The predicted failure loads correlate well with reported test results. Utilizing existing test data for composite bonded joints, it was found that the critical J_1 values in the first ply of the parent laminates are almost constant. The merit of the J_1 failure criterion is that it is valid for various environmental conditions, loading conditions, and surface ply orientations.

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FAILURE ANALYSIS OF COMPOSITE BONDED JOINTS

Hsi Chin Tsai
James Alper
David Barrett

Naval Air System Command
Structures Division (Code 4.3.3.1)
Patuxent River, Maryland, 20670, USA

Abstract

Because of the ineffectiveness of the commonly used failure criteria, current analysis methods fail to accurately predict the strength of bonded composite joints. This analytical shortfall results in overly conservative joint designs. In a composite bonded joint, failure typically occurs in the first ply of the parent laminate near the stress singularity. In this study an average strain approach is used to analyze this area and the first strain invariant failure criterion, also called the J_1 failure criterion, is adopted to predict the failure load of composite bonded joints. The analysis is based on a plane strain two-dimensional finite element model, which includes both the effects of geometric and material nonlinearity. The predicted failure loads correlate well with reported test results.

Utilizing existing test data for composite bonded joints, it was found that the critical J_1 values in the first ply of the parent laminates are almost constant. The merit of the J_1 failure criterion is that it is valid for various environmental conditions, loading conditions and surface ply orientations.

Nomenclature

U_d	dilatational energy density
$\varepsilon_1,\varepsilon_2,\varepsilon_3$	total normal strains
ΔT	temperature change from cure temperature
α	thermal expansion coefficient
E	Young's modulus
υ	Poisson's ratio
J_1	first invariant of mechanical strain
J^m_{cr}	critical value of J_1 for matrix
J^c_{cr}	critical value of J_1 for a composite ply
Lp	overlap (length of bond)
t_{adh}	thickness of adhesive

Introduction

Adhesive bonding offers many advantages over traditional fastening methods including cost savings, reduced assembly time, high strength to weight ratios, corrosion resistance and fatigue resistance. However, this method of fastening has not been widely applied because quantitative procedures have not yet been developed that can accurately model the failure processes. Thus, the ability to predict the strength of composite bonded joints has been the object of many studies.[1-10] Up until now, the analysis methods fail to predict the strength of composite bonded joints and thus engineers resort to overly conservative designs.

The objective of this study is to develop an analysis method to predict the failure mode and failure load of composite bonded joints. To achieve this objective certain conditions must be met. First, the analysis method must be capable of predicting the stresses and strains in the area of a stress singularity. Material and geometrical non-linearities must be included in this analysis method. Second, due to the complexity of composite failure modes, a robust and accurate failure criteria to predict the composite joint failure must be developed. Finally, sufficient test data is needed to validate the analysis method and failure criteria.

In general, for composite double lap joints, the primary failure mode is a cohesive failure in the first ply of the parent laminate.[11] Another less dominant failure modes are cohesive failure in the adhesive layer and adhesive failure between adhesive layer and first ply of parent laminate. This study will concentrate on predicting the failure load due to a first ply cohesive failure in the parent laminate. The commercially available COSMOS/M computer code was selected to perform this analysis. An average strain approach near the stress singularity and the first strain invariant failure criterion [12], also called J_1 failure criterion, were adopted to predict the failure loads of composite bonded joints. A two-dimensional plane strain model was used to predict the stresses and strains near the singularity to validate the failure criterion.

J_1 Failure Criterion for Polymer Matrix

It has been proposed that polymer matrix materials fail either by matrix yielding or by matrix microcavitation.[13-15] Matrix yielding is related to distortional deformations, while microcavitation is related to dilatational behavior (i.e. volume effect). Two different failure criteria are proposed to predict these failure modes. First, the dilatational energy density criterion assumes that microcavitation occurs in the matrix material of a composite when the dilatational energy density reaches a critical value at any point of the matrix. Second, distortional energy density criterion assumes that matrix yielding occurs when distortional energy density of the matrix, reaches a critical value at any point of matrix. For composites under tensile loading, microcavitation failure in the matrix always occurs first. Thus, the dilatational energy density criterion will be used to predict the first ply cohesive failure of composite double lap joints under tensile loading. Since the dilatational energy density criterion of a matrix is valid only when a positive volume change of the matrix occurs, it is more appropriate to use the first invariant of the mechanical strain tensor as a parameter to predict the matrix failure. The dilitational energy density (U_d) can be computed from

$$U_d = E_m * (J_1^m)^2/6*(1-2*\nu_m) \tag{1}$$

where the matrix first invariant of the mechanical strain J_1^m is

$$J_1^m = \varepsilon_1^m + \varepsilon_2^m + \varepsilon_3^m - 3\alpha_m \Delta T$$

and ε_1^m,ε_2^m and ε_3^m are the total matrix normal strains in the x_1, x_2 and x_3 directions respectively, α_m is the coefficient of thermal expansion for the matrix, ΔT is the change in temperature, E_m is the Young's modulus for the matrix and ν_m is the Poisson's ratio of matrix.

From equation (1), it can be seen that the first invariant of the mechanical strain (i.e. J_1^m) can be used as a failure parameter. Thus, the failure criterion for matrix microcavitation can be stated as follows:

$$J_1^m \geq J^m_{cr} \tag{2}$$

where J^m_{cr} is the critical value of the first invariant for matrix microcavitational failure.

J_1 Failure Criterion for a Composite Ply

In a composite ply, there are regions in the matrix where the state of stress and strain will not be perturbed by the neighboring fibers. The strains of these matrix regions may be assumed to be approximately the same as the composite ply strains. We propose that when these matrix regions fail, the whole composite ply ultimately fails. Based on this assumption, a J_1 failure criterion for a composite ply may be proposed as follows:

$$J^c_1 \geq J^c_{cr} \tag{3}$$

where J^c_1 is the first invariant of mechanical strain for a composite ply and J^c_{cr} is the critical value of J_1 for composite ply failure. It can be proved that

$$J^c_1 = \varepsilon^c_1 + \varepsilon^c_2 + \varepsilon^c_3 - (\alpha^c_{11} + \alpha^c_{22} + \alpha^c_{33})\Delta T \tag{4}$$

where ε^c_1, ε^c_2 and ε^c_3 are the total composite normal strains in the x_1, x_2 and x_3 directions respectively and α^c_{11}, α^c_{22} and α^c_{33} are thermal expansion coefficient of the composite.

Since this study is not attempting to predict the progression of failure, it is understood that the solution proposed here is an approximate solution. Thus, J^c_{cr} is approximately J^m_{cr}.

Failure at Singularity

Stress and strain singularities exist at the surface edges between parent laminates and adhesive layers, and strap laminate and adhesive layer. Similar to point stress and average stress approaches[16], an average strain approach will be used to obtain J^c_1 values at the singularity. The characteristic length used to average the strains from the singularity site is assumed to be one lamina thickness of the composite[17].

The following will concentrate on developing J^c_1 critical values to see if J^c_{cr} is constant or nearly constant.

Finite Element Analysis of Composite Double Lap Joints

Existing Test Data[11]

Table 1 summarizes information concerning the composite double lap joint specimens. Note that three types of adhesive systems were used, namely, FM-300 autoclave cure, FM-300 oven cure and FM-300-2 oven cure. Figure 1 and Figure 2 show the thick adherend shear stress-strain curves of these adhesive systems under 75°F/Dry and –65° F/Dry conditions. The material for the adherend is IM7/977-3. Strap laminates

consisted of $[0]_6$, while the parent laminates were composed of plies with different orientations such as $[45,-45,0,90,0,90]_s$, $[90,0,90,0,45,-45]_s$ and $[0,90,0,90,45,-45]_s$. Tables 2 to 5 list the test failure shear stress of composite double lap joints with different overlap, surface ply (i.e. ply bonded with adhesive) and adhesive thickness for different adhesive systems and environmental conditions. Note that only the test data with adhesive thickness less than 0.0126 inch were selected for evaluation and analysis. J_{cr}^c obtained through these test data will be used to predict the failure loads of composite double lap joints with thicker adhesive thickness. Also, note that the adhesive thickness and test failure stresses shown in these tables and the subsequent tables are an average values of a group of specimens.

Finite Element Model of Composite Double Lap Joint

The composite double lap joints were modeled as two-dimensional plane strain problems. The analysis included the effects of geometric and material nonlinearities.

Nonlinear behavior of the adhesive systems, as shown in Figure 1 and Figure 2, were represented by equivalent elastic-plastic stress strain curves[1] as shown in Figure 3. The stress strain curve of each adhesive system will then be represented by three parameters, namely, Young's modulus, Poisson's ratio and the yield stress as shown in Figure 4. Due to symmetric conditions, only a quarter of the double lap joint was modeled. A typical finite element model for the composite double lap joint is shown in Figure 5. To comply with the average strain approach near the singularity site, the mesh size in the X direction at the junction of parent laminate, adhesive and strap laminate is equal to a ply thickness. Away from the stress singularity, the larger mesh sizes were used. For both parent laminate and strap laminate, the element size in Y-direction is equal to a ply thickness. The adhesive layer was modeled as one row of elements. Symmetric boundary conditions were assumed on both the left and bottom side of the model. Tensile loading was applied to the right side boundary nodes.

Evaluation of Various Failure Criteria

The data in Table 6 was used for the analysis. The analytical results were used to evaluate various failure criteria. The failure criteria that were evaluated were maximum principal stress, Von-Mises stress, critical J_I, Von-Mises strain, maximum principal strain and maximum peel stress. The results of the evaluation are tabulated in Table 7, 8 and 9. It can be seen from these tables that only the J_I failure criterion appears to be nearly constant. This conclusion is reinforced by Figure 6.

J_I Failure criterion Evaluation with Various Adhesive Systems

Employing test data from Tables 2 through 5, the J^c_I critical values of composite double lap joints with different adhesive systems were obtained from finite element analysis and are tabulated in Tables 10 and 11. These J^c_I critical values were also plotted as shown in Figure 7. From the Tables and Figure 7, it can be seen that J^c_I critical values may be approximated as a constant value. In this study, J^c_{cr} is assumed equal to 0.01298. Table 12 shows the J^c_{cr} for three different adhesive systems. It can be seen that J^c_{cr} is almost independent of the adhesive system being used in composite bonded joints. As a summary from this study, one can conclude that J^c_I critical values are independent of the adhesive system, the surface ply orientation, the environmental conditions and the overlap length.

Failure Prediction of Composite Double Lap Joints

Using J^c_{cr} equal to 0.01298, the predicted failure loads for the test specimens shown in Tables 2 through 5 were calculated. The predicted failure loads are shown in Tables 13 and 14. The results are also plotted in Figures 8 and 9. As can be seen from these tables and the figures, the predicted failure loads correlate well with the test results. The J_I failure criteria were also applied to predict the failure loads of composite double lap joints with thicker adhesive layers. In general, two or three elements were used to model the thicker adhesive layers in the Y-direction. The test data and the predicted failure loads are listed together in Tables 15 and 16 and are also plotted in Figures 10 and 11. It can be seen that the predicted failure loads for 75 °F/Dry compare to within 15% of the test data. For the –65 °F/Dry condition, the maximum discrepancy between predicted failure loads and test data is approximately equal to 27%. The reasons for this large discrepancy may be due to three-dimensional effects that were not included in current model or the test data may be unreliable for the thicker adhesive layer under a -65°F/Dry condition. To assure a prediction to within 15% of the true value, the adhesive thickness should not be greater than 0.016 inch. Predictions based on A4EI code [1,18] were also included in these tables and

figures. It can be seen that A4EI over predict the failure loads by a factor of two.

Concluding Remarks

A new failure criterion was applied to the analysis of composite bonded joints. The following conclusions are drawn from this study:

- Utilizing composite double lap joint test data, it was found that the J_1 values at failure are nearly a constant and are independent of the surface ply orientations, environmental conditions and adhesive systems.
- Based on the J_1 failure criteria, the predicted failure loads correlate well with test results for adhesive thickness less than 0.016 inch. For adhesive thickness greater than 0.016 inch, a three dimensional model may be needed.

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Table 1: Description of Composite Double Lap Joints

$t_{adh} \leq .0126$ in.

Adhesive Systems & Adherend Materials
- FM-300 Oven Cure
- FM-300-2 Oven Cure
- FM-300 Autoclave Cure
- Adherend Material: IM7/977-3
- Parent Laminates: $[45,-45,0,90,0,90]_s$, $[90,0,90,0,45,-45]_s$, $[0,90,0,90,45,-45]_s$
- Strap Laminates: $[0]_6$

Table 2: Test Specimen Configurations and Test Data

Adhesive System: FM-300 Autoclave

75 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
0.5	45	0.0059	5251
0.5	90	0.0067	3400

-65 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
0.5	45	0.0063	3520
0.5	90	0.0069	2580

Table 3: Test Specimen Configurations and Test Data

Adhesive System: FM-300 Autoclave

75 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0073	2611
1.5	45	0.0107	1810

-65 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0071	1750
1.5	45	0.0096	1350

Table 4: Test Specimen Configurations and Test Data

Adhesive System: FM-300

75 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0125	2540
1.0	90	0.0120	1658

-65 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0124	1668
1.0	90	0.0119	1465

Table 5: Test Specimen Configurations and Test Data

Adhesive System: FM-300-2

75 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0125	2234
1.0	90	0.0126	1593

-65 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
1.0	45	0.0125	1711
1.0	90	0.0118	1274

Table 7: Failure Criteria Evaluation for Composite Double Lap Joints

Parent Laminate: $[90,0,90,0,45,-45]_s$,IM7/977-3

(Overlap Length = 0.5 Inch)

Failure Criterion	-65 Deg. F Dry	75 Deg. F Dry	Ratio*
Max. Princ. Stress	22.38 Ksi	20.72 Ksi	0.9300
Von-Mises Stress	15.63 Ksi	13.66 Ksi	0.8700
J_1 Strain	0.01242	0.01382	1.1100
Von-Mises Strain	0.01657	0.01894	1.1400
Max. Prin. Strain	0.01508	0.01709	1.1300
Max. Peel Stress	5.10 Ksi	6.27 Ksi	1.2200

* Ratio = (Result of 75 Deg. F) ÷ (Result of -65 Deg. F)

J_1 = Sum of Principal Mechanical Strains.

Table 6: Test Specimen Configurations and Test Data

Adhesive System: FM-300, Autoclave

75 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
0.5	45	0.0059	5251
0.5	90	0.0067	3400
0.5	0*	0.0078	5749

-65 Deg. F / Dry

Lp (in.)	Surface Ply (Deg.)	t_{adh} (in.)	Failure Stress (Psi)
0.5	45	0.0063	3520
0.5	90	0.0069	2580
0.5	0*	0.0075	3749

* First ply cohesive failure is not as dominant as 45 deg. and 90 deg. surface plies.

Table 8: Failure Criteria Evaluation for Composite Double Lap Joints

Parent Laminate: $[45,-45,0,90,0,90]_s$, IM7/977-3

(Overlap Length = 0.5 Inch)

Failure Criterion	-65 Deg. F Dry	75 Deg. F Dry	Ratio*
Max. Princ. Stress	30.02 Ksi	32.89 Ksi	1.1300
Von-Mises Stress	21.08 Ksi	24.25 Ksi	1.1800
J_1 Strain	0.01272	0.01230	0.9700
Von-Mises Strain	0.01876	0.02070	1.1000
Max. Prin. Strain	0.01510	0.01664	1.1000
Max. Peel Stress	7.24 Ksi	5.60 Ksi	0.7700

* Ratio = (Result of 75 Deg. F) ÷ (Result of -65 Deg. F)

J_1 = Sum of Principal Mechanical Strains.

Table 9: Failure Criteria Evaluation for Composite Double Lap Joints

Parent Laminate: $[0,90,0,90,45,-45]_s$,IM7/977-3
(Overlap Length = 0.5 Inch)

Failure Criterion	-65 Deg. F Dry	75 Deg. F Dry	Ratio*
Max. Princ. Stress	149.30 Ksi	241.8 Ksi	1.6200
Von-Mises Stress	137.30 Ksi	232.5 Ksi	1.6900
J_1 Strain	0.01375	0.01395	1.0100
Von-Mises Strain	0.0968	0.01186	1.2200
Max. Prin. Strain	0.0830	0.01103	1.3300
Max. Peel Stress	7.23 Ksi	5.80 Ksi	0.8000

* Ratio = (Result of 75 Deg. F) ÷ (Result of -65 Deg. F)
J_1 = Sum of Principal Mechanical Strains.

Table 10: J_1 Strain at Failure for Various Adhesive Systems

(75 Deg. F / Dry, t_{adh} < 0.0126 in.)

Lp (In.)	Adhesive System	Surface Ply (Deg.)	J_1^c Value	J_1^c/J^c_{cr}
1.0	FM-300-2	45.0	13.32	1.03
1.0	FM-300-2	90.0	13.22	1.02
1.0	FM-300	45.0	13.33	1.03
1.0	FM-300	90.0	13.54	1.04
0.5	FM-300-Auto	45.0	12.30	0.95
1.0	FM-300-Auto	45.0	13.02	1.00
1.5	FM-300-Auto	45.0	13.57	1.05
0.5	FM-300-Auto	90.0	13.82	1.07

J^c_{cr} = Average J_1 Values of -65 Deg. F / Dry and 75 Deg. F / Dry = 0.01298

Table 11: J_1 Strain at Failure for Various Adhesive Systems

(-65 Deg.F/Dry, t_{adh} < 0.0126 in.)

Lp (In.)	Adhesive System	Surface Ply (Deg.)	J_1^cValue	J_1^c/J^c_{cr}
1.0	FM-300-2	45.0	0.01204	0.93
1.0	FM-300-2	90.0	0.01214	0.94
1.0	FM-300	45.0	0.01222	0.94
1.0	FM-300	90.0	0.01371	1.06
0.5	FM-300-Auto	45.0	0.01272	0.98
1.0	FM-300-Auto	45.0	0.01263	0.97
1.5	FM-300-Auto	45.0	0.01370	1.06
0.5	FM-300-Auto	90.0	0.01240	0.96

J^c_{cr} = Average J_1 Values of -65 Deg. F / Dry and 75 Deg. F / Dry = 0.01298

Table 12: Summary of $J_1{}^c$ Critical Strains

($t_{adh} \leq$ 0.0126 in.)

Adhesive System	J_1^c
FM-300-02	0.01268
FM-300-Autoclave	0.01302
FM-300	0.01320

J^c_{cr} = Average of J_1 from 16 Test Data = 0.01298

The Results Show that $J_1{}^c$ Critical Is Independent of Adhesive Systems

Table 13: Comparison between Predicted Failure Stresses And Average Test Results
(75 Deg.F/Dry, J^c_{cr} = 0.01298, 0.005 in. < t_{adh} < 0.0126 in.)

Lp (In.)	Adhesive System	Surface Ply (Deg.)	Prediction (psi)	Average Test Data (psi)	Ratio*
1.0	FM-300-2	45.0	2117	2234	0.95
1.0	FM-300-2	90.0	1566	1593	0.98
1.0	FM-300	45.0	2347	2540	0.92
1.0	FM-300	90.0	1569	1658	0.95
0.5	FM-300-Auto	45.0	5705	5251	1.09
1.0	FM-300-Auto	45.0	2590	2611	0.99
1.5	FM-300-Auto	45.0	1613	1810	0.89
0.5	FM-300-Auto	90.0	3120	3400	0.92

*Ratio = Prediction / Average Test Data

Table 14: Comparison between Predicted Failure Stresses And Average Test Results
(-65 Deg.F/Dry, J^c_{cr} = 0.01298, 0.005 in. < t_{adh} < 0.0126 in.)

Lp (In.)	Adh. System	Surface Ply (Deg.)	Prediction (psi)	Average Test Data (psi)	Ratio*
1.0	FM-300-2	45.0	1880	1711	1.10
1.0	FM-300-2	90.0	1413	1274	1.11
1.0	FM-300	45.0	1880	1668	1.13
1.0	FM-300	90.0	1351	1465	0.92
0.5	FM300-Auto	45.0	3594	3520	1.02
1.0	FM300-Auto	45.0	1842	1750	1.05
1.5	FM300-Auto	45.0	1255	1350	0.93
0.5	FM300-Auto	90.0	2715	2580	1.05

*Ratio = Prediction / Average Test Data

Table 15: Comparison between Predicted and Experimental Results for Composite Double Lap Joints Using Thicker Adhesive Layers
(75 Deg.F/Dry, FM-300-Autoclave, 45 Deg. Surface Ply, J^c_{cr} = 0.01298)

Lp (in.)	t_{adh} (in.)	Test Failure Stress (psi)	Prediction (J_1) (psi)	Prediction (A4EI)(psi)
0.5	0.0150	5100	4368	N.A
0.5	0.0196	3845	4320	N.A
1.0	0.0167	2029	2326	3940
1.0	0.0240	2073	2363	4696
1.5	0.0171	1739	1560	2667
1.5	0.0300	1654	1641	3253

Table 16: Comparison between Predicted and Experimental Results for Composite Double Lap Joints Using Thicker Adhesive Layers
(-65 Deg. F/Dry, FM-300-Autoclave, 45 Deg. Surface Ply, J^c_{cr} = 12.98-03)

Lp (in.)	t_{adh} (in.)	Test Failure Stress (psi)	Prediction (J_1) (psi)	Prediction (A4EI)(psi)
0.5	0.0163	3483	3690	6384
0.5	0.0195	3068	3722	7449
1.0	0.0170	1630	1966	3376
1.0	0.0217	1569	1988	4112
1.5	0.0159	1428	1305	2257
1.5	0.0316	1074	1350	2763

Figure 1: Shear Stress Strain Curves for Various Adhesive Systems

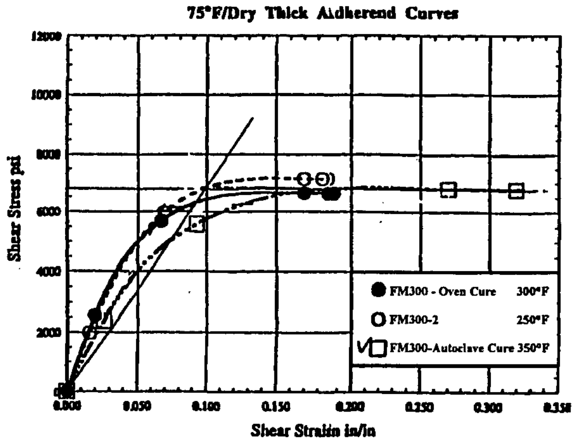


Figure 4: Elastic-Ideally-Plastic Material

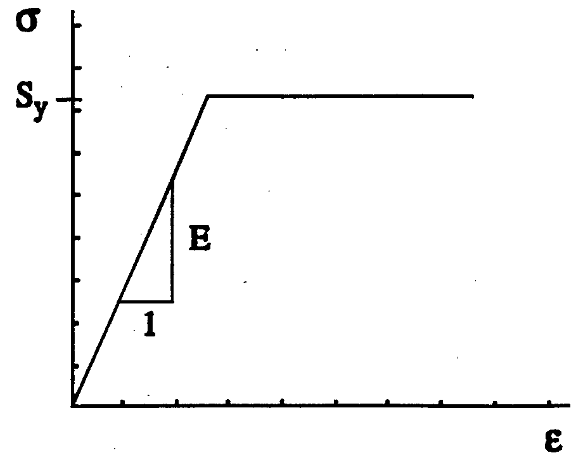


Figure 2: Shear Stress Strain Curves for Various Adhesive Systems

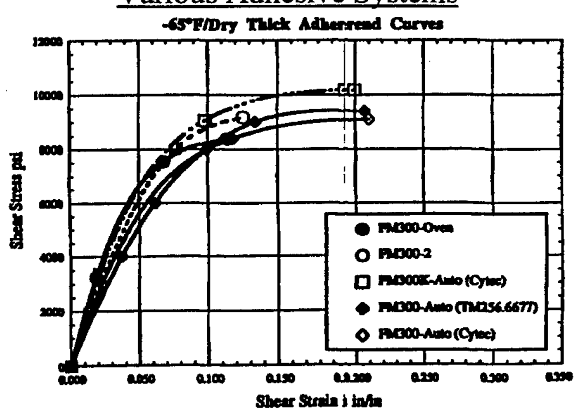
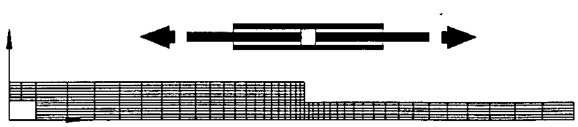


Figure 5: Typical Finite Element Model of Composite Double Lap Joints

(Overlap Length = 0.5 in.)



- Analytical Tool – COSMOS/M
- Analytical Model – 2-D Plain Strain Model
- Analytical Material Model – Bi-Linear Model

Figure 3: Analytical Representation for Actual Adhesive Material

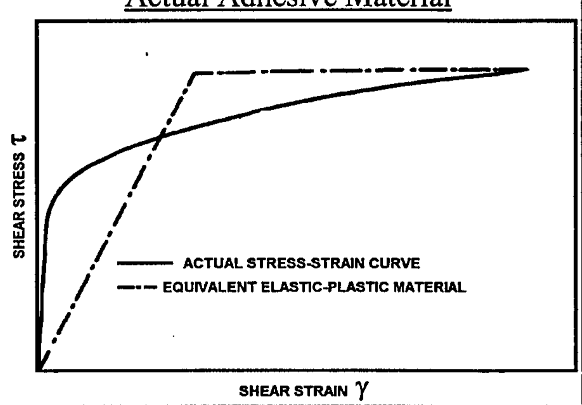


Figure 6: J1 Strain Criteron Evaluation

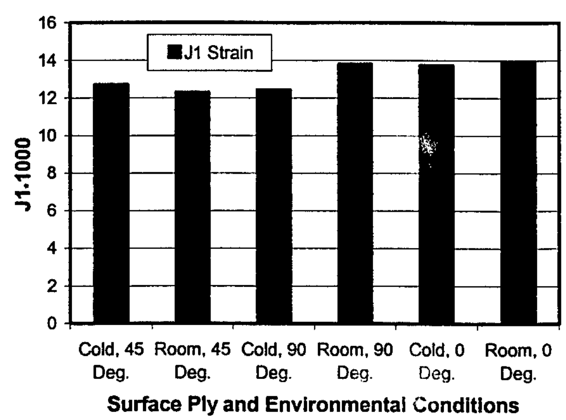


Figure 7: J1 at Failure Loads for Various Adhesive Systems

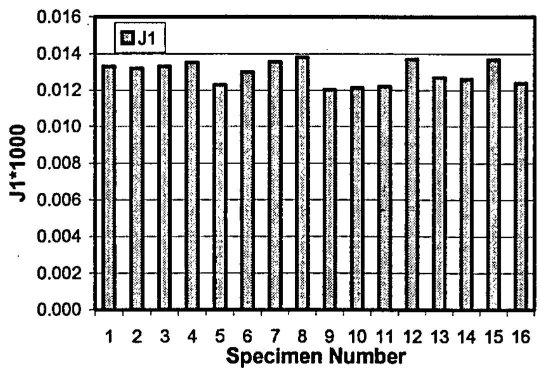


Figure 8: Comparison Between Predicted and Experimental Results (75 Deg.F/Dry)

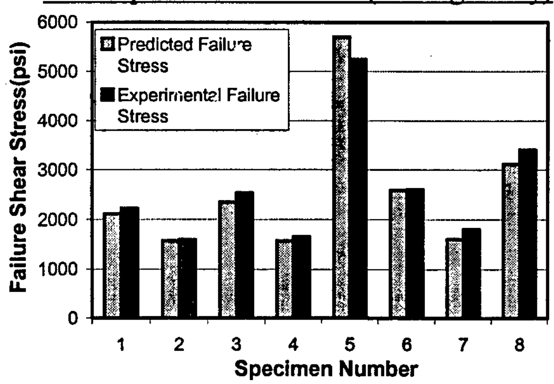


Figure 9: Comparison Betweeen Predicted and Experimental Results (-65 Deg.F/Dry)

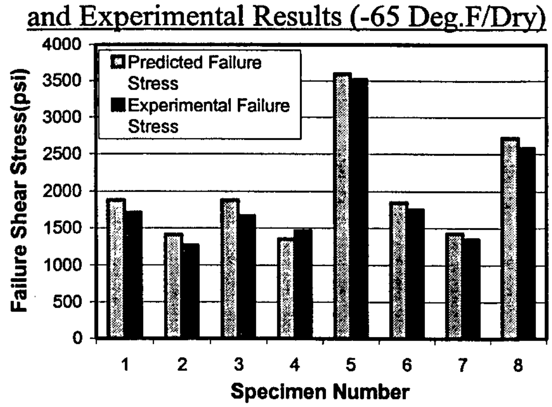


Figure 10: Comparison Between Predicted and Experimental Results for Composite Double Lap Joints Using Thicker Adhesive Layers (75 Deg.F/Dry)

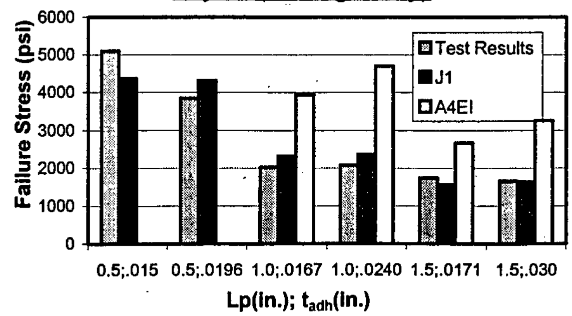


Figure 11: Comparison Between Predicted and Experimental Results for Composite Double Lap Joints Using Thicker Adhesive Layers (-65 deg/dry)